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Spatial distribution and comprehensive evaluation of emerging organic pollutants in effluents from wastewater treatment plants in northern cities of China

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ABSTRACT

This study investigated the occurrence of 42 pharmaceuticals and personal care products (PPCPs), 4 steroid estrogens and 15 phthalates in the effluents of 12 wastewater treatment plants (WWTPs) in 11 northern cities of China. Of the 61 emerging organic pollutants (EOPs), 49 EOPs were detected, and the detection frequencies of 18 compounds were over 90%. PPCPs were the predominant species and contributed to approximately half of the total EOP concentrations in the most of the investigated WWTPs. The four EOPs with the highest mean concentrations of the 49 were metoprolol (798.0 ng L^{-1}), carbamazepine (597.5 ng L^{-1}), sulpiride (543.5 ng L^{-1}) and dimethyl phthalate (502.6 ng L^{-1}). The levels of some detected EOPs showed positive correlations with the total nitrogen level. In the ecological risk evaluation, roxithromycin, diclofenac acid, sulfamethoxazole, ofloxacin, clindamycin, sulpiride, ibuprofen, 17α-ethynylestradiol, and dimethyl phthalate exhibited high or medium risks in the effluents. Four representative compounds, diclofenac acid, roxithromycin, sulfamethoxazole, and dimethyl phthalate, could be selected as indicators for predicting overall EOP levels.

Keywords: Emerging organic pollutants; Pharmaceuticals and personal care products; Endocrine disrupting chemicals; Phthalates; Wastewater treatment plants; Steroid estrogens

1. Introduction

The occurrence of emerging organic pollutants (EOPs) is of concern because of their ubiquitous presence in the environments and potential to cause undesirable harmful effects to ecology or human beings [1,2].

Pharmaceuticals and personal care products (PPCPs) include human and veterinary drugs (e.g., antibiotics, hormones, hypnotics, anticonvulsants, analgesics, antidepressants, contraceptives, and lipid regulators) and their subsequent metabolites. PPCPs also include shampoo, hair dyes, moisturizers, fragrances, lipsticks, sunscreen, fungicides and insect repellent. Exposure to PPCPs can result in disruptions of the endocrine system and chronic toxicity in humans and other species [3]. The existence of antibiotics in the environment can also lead to the accumulation of antibiotic resistant genes and resistant bacteria, which reduces the therapeutic potential of antibiotics against human and animal pathogens [4].

Endocrine disrupting chemicals (EDCs) are natural or artificial compounds that can interfere with the endocrine system inducing developmental and reproductive toxicity in mammals and aquatic species [5,6]. EDCs include a wide range of pollutants, such as natural and artificial hormones, industrial and household chemicals, and drugs with hormonal side effects. Natural steroid estrogens (e.g., 17a-ethinylestradiol, 17β-estradiol, estrone, and estriol), which are present in the excrement of human beings and livestock, are typical EDCs from natural sources [2]. Phthalates, which are mainly used as plasticizers (for the manufac-

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ture of polyvinylchloride plastics) and solvents, are another class of widely occurring EDCs. Some phthalates (such as dimethyl phthalate, dibutyl phthalate, dioctyl phthalate and di(2-ethylhexyl)octyl phthalate) were on the priority pollutant list of the European Union, the United States and China [7,8].

Wastewater treatment plants (WWTPs) are reported to be a major pathway for the disposal of these EOPs into aquatic environments because of the incomplete elimination of these EOPs in WWTPs [9–11]. Extensive studies have investigated the occurrence of PPCPs, steroid estrogens and phthalates in WWTP effluents, as summarized in Table 1 [12–43]. These EOP concentrations ranged from below the detection limits to several thousands of ng L^{-1}. These background data are essential for the further fate assessment and risk evaluation of the EOPs in aquatic environments. However, most of the studies focused either on limited species of EOPs or certain regions [1,12,13]. As a result, it is difficult to conduct a comparison of the EOP levels between different species of EOPs or between regions in different reports. Moreover, the relationships between different EOPs or between EOPs and water characteristics have seldom been discussed. Comparable data and relationships between different EOPs or between EOPs and water characteristics are important for evaluating the overall potential ecological risks of EOPs in WWTP effluents and the receiving water bodies.

In this study, we selected 11 typical northern cities in China, including Harbin, Changchun, Beijing, the downtown area of Tianjin, the Binhai district of Tianjin, Shijiazhuang, Qinhuangdao, Qingdao, Luohe, Taiyuan, Xi'an, and Baotou (Table 2 and Fig. 1), all of which have high population densities and are traditionally heavy industry and energy bases. Shortage and uneven distribution of water resources are the main factors restricting the economic development of these cities. The release of EOPs through the discharge of WWTP effluents is a serious problem in these cities. However, investigation of EOPs in the northern cities of China has been limited. Therefore, the occurrence, spatial characteristics, and potential environmental risks of 42 PPCPs and 19 EDCs (4 steroid estrogens and 15 phthalates) were simultaneously investigated in the WWTP effluents in the 11 cities. The relationships between different EOPs and between the EOPs and water characteristics were investigated.

2. Material and methods

2.1. Sampling

From late April to early May 2017, we collected isochronous mixture effluent samples (four times a day) from 12 WWTPs located in the 11 northern cities of China (Table 2 and Fig. 1). Samples at each site were collected by mixing three grab samples collected. The effluent samples were filtered through a 0.45 μm membrane filter and stored at 4°C for further analysis within the next 24 h.

2.2. Chemicals and reagents

Antibiotic standards of sulfonamides (including sulfonamides, sulfamerazine, sulfisoxazole, sulfisomidin sodium, sulfamethoxypyridazine, sulfaquinoxaline, sulfamethazine, sulfadimethoxine, sulfamethoxazole, sulfamethizol, and sulfamonomethoxine), trimethoprim, tetracyclines (including tetracycline hydrochloride, chlorotetracycline hydrochloride, and oxytetracycline), penicilline G potassium salt, macrolides (including erythromycin, clarithromycin, roxithromycin, tylosin tartrate, and azithromycin), clindamycin hydrochloride, quinolones (including nalidixic acid, enrofloxacin, ciprofloxacin hydrochloride, ofloxacin, and norfloxacin), chloramphenicol, propranolol, carbamazepine, N,N-Diethylamino-3-methyl benzoyl amide (DEET), sulpiride, metoprolol, caffeine, antiphlogistic analgesics (including diclofenac acid, indomethacine, ketoprofen, buprofen, and mefenamic acid), dyslipidemia drugs (including bezafibrate, clofibric acid, and gemfibrozil), acetaminophen, and steroid estrogens (including estrone, 17β-estradiol, estriol, and 17a-ethinyl-estradiol) were purchased from Dr. Ehrenstorfer (Germany). Phthalate standards of dimethyl phthalate, diethyl phthalate, diisobutyl phthalate, dibutyl phthalate, dimethoxyethyl phthalate, diisohexyl phthalate, diethoxyethyl phthalate, di-N-pentyl phthalate, dihexyl phthalate, benzyl butyl phthalate, 1,2-benzenedicarboxylic acid, dicyclohexyl phthalate, di(2-ethylhexyl)octyl phthalate, dioctyl phthalate, and dinonyl phthalate were purchased from AccuStandard (USA). Stock solutions of all standard compounds were prepared in methanol. Working standard solutions were prepared with different concentrations (5, 10, 20, 50, 100, and 200 ng L^{-1}) by diluting the stock solution with methanol–water (25:75%, v/v). $^{13}C_6$-simeton, ^{13}C-phenacetin, ^{13}C-EM, D_6-GF, and D_8-CIP were used as internal standards for PPCPs. Estradiol-$^{13}C_6$, estradiol-d_2, and ethynylestradiol-$^{13}C_2$ were used as internal standards for steroid estrogens. Diphenyl phthalate, diphenyl isophthalate, and dibenzyl phthalate were used as internal standards for phthalates. High-performance liquid chromatography (HPLC)-grade solvents (methanol, acetonitrile, acetone, and formic acid) were purchased from DUKSAN, Korea. Ultrapure water (18.2 MΩ cm) was produced by a Milli-Q system (Millipore, France). Solid-phase extraction (SPE) cartridges (Oasis, HLB, 500 mg) were purchased from Waters Co. Ltd (USA).

2.3. Analysis methods

The EOPs in the water were concentrated through SPE. The cartridges were preconditioned with 10 mL of methanol (for extraction of PPCPs) or 10 mL of hexane (for extraction of EDCs), and 10 mL of ultrapure water. For the detection of antibiotics and other PPCPs, another 10 mL of acidic ultrapure water (pH 3.0 ± 0.1 for antibiotics and pH 4.5 ± 0. 1 for the other PPCPs) was used following the 10 mL of ultrapure water in the cartridge preconditioning. One liter of the filtered water samples was passed through the cartridge at a flow rate of 5–10 mL min^{-1}. After dehydration by air, the cartridges were eluted with 8 mL of methanol. Then, the 8 mL of methanol was concentrated to 1 mL under a gentle stream of nitrogen gas.

The 42 species of PPCPs and 4 steroid estrogens were analyzed using HPLC-tandem mass spectrometry (LC-20ADXR united with API3200 Qtrap, SHIMADZU Corporation) based on EPA Methods [44,45] and the references [46], and the phthalates were analyzed using a JMS-

Table 1
Occurrence of EOPs in the WWTP effluents in different countries

Categories	Selected compounds	Sampling site	Effluent (μg L^{-1})	References
Pharmaceuticals and personal care products (PPCPs)				
Analgesic and anti-inflammatory	Acetaminophen	Korea, Spain, WB[a], UK[b], Malaysia	ND[c]-11.733	[14–22]
	Diclofenac	Greece, Korea, Sweden, Switzerland, UK, WB, Malaysia	<0.001–0.69	[14–27]
	Ibuprofen	China, EU-wide[d], Korea, UK, US[e], WB	ND-55	[15,17–21,23–29]
	Ketoprofen	China, EU-wide, Korea, UK, WB	<0.003–3.92	[15,17,22,24,26,28,30]
	Mefenamic acid	EU-wide, Korea, UK, Malaysia	<0.005–0.45	[14,15,17,21]
Anticonvulsant	Carbamazepine	China, EU-wide, Korea, UK, WB	<0.005–4.60	[15,16,18–22,24,27,28,30,31]
	Sulpiride	China	0.077–0.220	[31]
Lipid regulator	Bezafibrate	China, EU-wide, Korea, UK, WB	0.03–2.15	[15,17–19,21,22,24,30,31]
	Clofibric acid	China, EU-wide, Korea, UK, WB	ND-0.33	[15,21,22,24,25,27]
	Gemfibrozil	EU-wide, Korea, WB	<0.0025–5.24	[15,17,21,22,24,25]
Antibiotic	Erythromycin	China, Spain, UK, WB	0.013–2.84	[17–19,21–23,26,31–34]
	Azithromycin	China	0.023–0.129	[33]
	Sulfamethoxazole	China, France, Korea, Spain, Sweden, Switzerland, UK, WB	<0.003–1.15	[15–17,21,22,24,31–35]
	Trimethoprim	China, EU-wide, Korea, UK	<0.01–3.05	[15–19,21,22,24,26,31]
	Amoxicillin	China, UK	0.002–0.0031	[19,33]
	Chloramphenicol	UK	<0.006–0.021	[18–20]
	Ciprofloxacin	Spain	ND-16.02	[30,32]
	Clarithromycin	China	0.026–0.123	[31]
	Ofloxacin	China, UK	0.01–2.285	[19,20,32,33,34]
	Oxytetracycline	China, UK	0.010–0.17	[19,34]
	Norfloxacin	China	0.009–1.162	[32,34]
	Roxithromycin	China	0.033–0.413	[31–34]
	Lincomycin	China	0.035–0.180	[31,34]
	Sulfadimethoxine	China	0.164–0.344	[20,31,34]
	Sulfamerazine	China	0.003–0.014	[20,31,33,34]
	Sulfapyridine	China, UK	0.019–0.455	[18,31,32]
β-Blocker	Metoprolol	China, Korea, Spain, Switzerland, UK, Malaysia	0.003–1.516	[15,17–21,31,36,37]
	Propranolol	UK	0.009–0.388	[18,19,23]
Nervous stimulant	Caffeine	China, EU-wide, Greek, Korea, UK	ND-43.50	[15,16,21,24–26,28,29]
Insect repellant	DEET[f]	China, EU-wide	0.61–15.8	[22,24]
Endocrine disrupting chemicals (EDCs)				
Steroid estrogen	Estrone	China, France, Germany, Italy, Korea, Sweden, US	<0.001–0.116	[15,19,20,27,38–40]
	Estradiol	China, France, Germany, Italy, Korea, Sweden, US	<0.001–0.051	[15,19,27,38–40]
	17α-Ethynylestradiol	China, France, Germany, Italy, Sweden, US	<0.001–0.484	[19,20,27,38–40]
	Estriol	China, Korea, Germany	ND	[15,39,40]
Phthalate	Dibutyl phthalate	Austria, China	ND-4.13	[41,42]
	Diethylhexyl phthalate	Austria, China, US	0.0001–54.0	[30,41–43]
	Dimethyl phthalate	Austria, China	ND-60	[41–43]

Notes: [a]: WB, Western Balkan Region (including Bosnia and Herzegovina, Croatia and Serbia); [b]: UK, the United Kingdom; [c]: ND, not detected; [d]: EU-wide, including Austria, Belgium, Czech Republic, Cyprus, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Lithuania, Netherlands, Portugal, Slovenia, Spain, Sweden, and Switzerland; [e]: US, the United States; [f]: DEET, N,NDiethylamino-3-methyl benzoyl amide.

Table 2
Description of the twelve investigated WWTPs

Name	City	Province	Daily flow[a] (Ratio[b])	Major treatment process
HLJ	Harbin	Heilongjiang	100 (25%)	Multistage AO[c]
JL	Changchun	Jilin	390 (5%)	AAO
BJ	Beijing	Beijing	40 (0)	Oxidation ditch-AAO
TJ1	Tianjin	Tianjin	450 (20%)	AAO
TJ2	Tianjin-Binhai	Tianjin	550 (40%)	Multistage AO[d]
HB1	Shijiazhuang	Hebei	100 (90%)	Carrousel oxidation ditch
HB2	Qinhuangdao	Hebei	70 (10%)	AAO
SD	Qingdao	Shandong	100 (80%)	SBR-ICEAS[e]+AAO
HN	Luohe	Henan	80 (50%)	Oxidation ditch
SX	Taiyuan	Shanxi	160 (0)	AAO
SHX	Xi'an	Shaanxi	200 (30%)	Oxidation ditch+ multistage AO
NMG	Baotou	Inner Mongolia	58 (0)	AAO

Notes: [a]: Average daily flow ($\times 10^3$ m^3 day^{-1}); [b]: The volume ratio of industrial wastewater to sewage; [c]: AAO, Anaerobic/Anoxic/Oxic; [d]: AO, Anoxic/Oxic; [e]: SBR-CEAS, Sequencing Batch Reactor-Intermittent Cycle Extended Aeration.

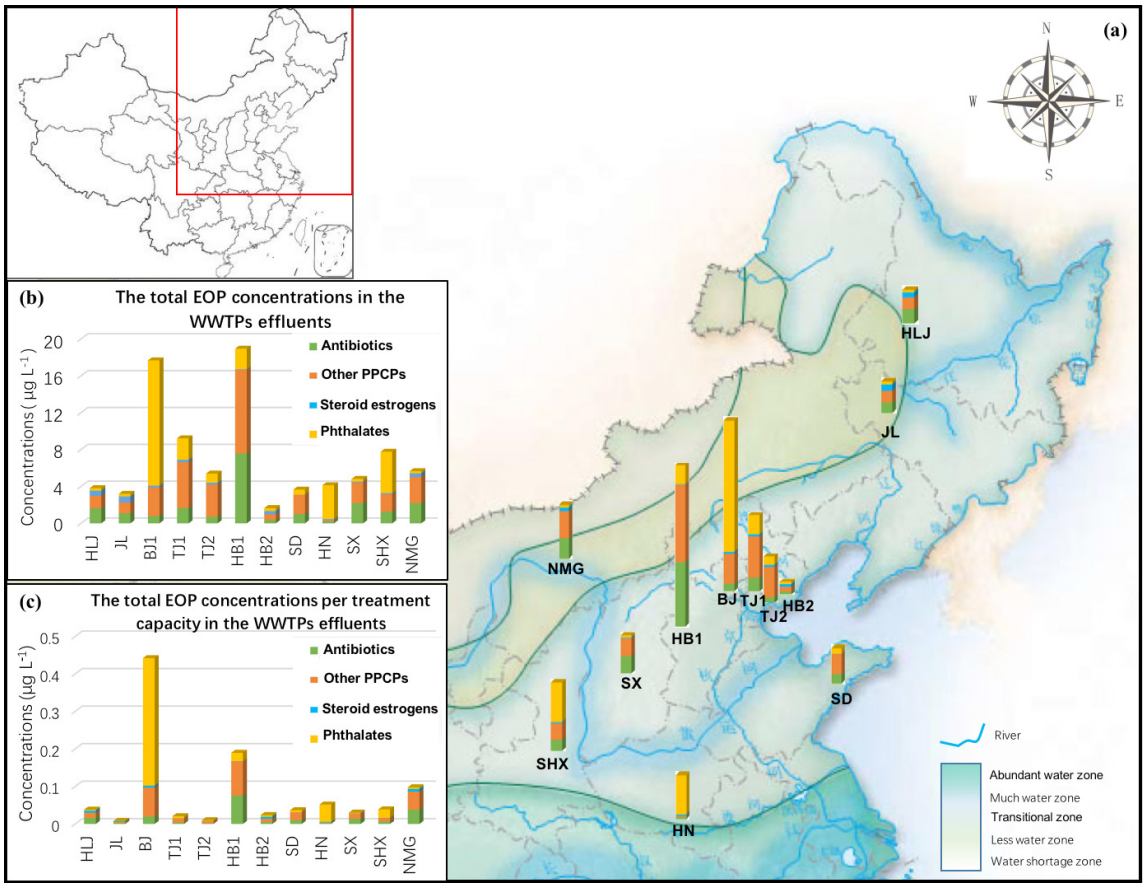

Fig. 1. Locations and levels of EOPs in effluents of the 12 WWTPs.

Q1000GC with Agilent 7890A [47]. The limits of detection and limits of quantitation were calculated by using a signal-to-noise ratio of 3 and 10, respectively. The linear range of the calibration curves varied for different chemicals, and the determination coefficients (R^2) of the regression curves were >0.995 for all the compounds. Recoveries were typically above 70%, triplicates were adopted and standard deviations were less than 10%.

The chemical oxygen demand (COD), biological oxygen demand (BOD) and concentrations of the total suspended

solids (TSS), phosphorus, ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen in the effluent were determined according to standard methods [48]. The ultraviolet light absorbance at 254 nm (UV_{254}) was analyzed using a spectrophotometer (Jasco V-350 UV/VIS, Japan). The total organic carbon (TOC) was detected with a TOC-VCPH instrument (Shimadzu, Japan). The concentrations of anions (F^-, Cl^-, SO_4^{2-}, and Br^-) were detected with an ion chromatograph (DX600, DIONEX, USA). Statistical analysis was conducted using IBM SPSS Statistics (Version 20) and Origin software (Version 8.0, Origin Lab, USA).

2.4. Environmental risk assessment

A risk quotient (RQ) was used to define the potential ecological risk of a given chemical relative to the aquatic environment, as shown in Eq. (1).

$$RQ = \frac{MEC_i}{PNEC_i} \quad (1)$$

where MEC_i is the measured environmental concentration of a chemical, and $PNEC_i$ is the predicted no-effect concentration of the chemical. Based on the European Union Technical Guidance Document, the PNEC is calculated by dividing the lowest short-term lethal (effective) concentration 50 ($L(E)C_{50}$) or long-term no observed effect concentration (NOEC) value by an appropriate assessment factor (AF) [49]. According to the literature and ecotoxicology database (ECOTOX) on the USEPA website (https://cfpub.epa.gov/ecotox/), the values of $L(E)C_{50}$ (or NOEC) and AFs of the EOPs with high concentrations and toxicities in this study (including sulfamethoxazole, ofloxacin, roxithromycin, chloramphenicol, norfloxacin, enrofloxacin, clindamycin, mefenamic acid, clofibric acid, gemfibrozil, ibuprofen, bezafibrate, DEET, carbamazepine, sulpiride, metoprolol, diclofenac acid, 17α-ethynylestradiol, dimethyl phthalate, and diethyl phthalate) are presented in Table 3.

3. Results and discussion

3.1. Water quality of the 12 WWTP effluents

The physicochemical parameters of the effluent samples from the 12 WWTPs are listed in Table 4. Of the 12 effluent samples, the values of COD and BOD_5 were 1–50 mg L^{-1} (except HB2 of 74 mg L^{-1}) and 1–19 mg L^{-1}. Low BOD_5/COD ratios (0.03–0.26) indicate that the residual organic matter in these effluents was relatively hard to biodegrade. The specific ultraviolet absorbance (SUVA, SUVA = UV_{254}/TOC (L mg^{-1} m^{-1})) is an indicator showing the aromatic carbon content of organic matter in water, since this measurement has a strong linear correlation with the aromatic content obtained from nuclear magnetic resonance data for a wide range of natural organic matter isolates [64,65]. The SUVA values of the effluents were generally low, indicating that the organic matter in the WWTP effluents had low aromatic contents. Imai [66] reported that the organic matter in WWTP effluent generally had a low molecular weight and a great portion of hydrophilic contents. The concentration of total nitrogen (TN) varied among effluent samples. In many effluent samples, the total organic nitrogen accounted for a high portion of the TN. It was reported that most of the

Table 3
Toxicological data of the selected EOPs

Compound	$L(E)C_{50}$ or NOEC (μg L^{-1})	Trophic level	AF	PNEC (ng L^{-1})	Reference
Sulfamethoxazole	1530	–	1000	1530	[50]
Ofloxacin	1440	–	1000	1440	[51]
Roxithromycin	10	1	100	100	[52]
Chloramphenicol	10000	2	50	200000	[51]
Norfloxacin	9.8	3	10	980	[53]
Enrofloxacin	3100	–	1000	3100	[51]
Clindamycin	100	1	100	1000	[54]
Mefenamic acid	3950	–	1000	3950	[55]
Clofibric acid	10	3	10	1000	[56]
Gemfibrozil	100	1	100	1000	[57]
Ibuprofen	10	3	10	1000	[51]
Bezafibrate	7620	–	1000	7620	[58]
DEET[a]	50	3	10	5000	ECOTOX[b]
Carbamazepine	25	3	10	2500	[59]
Sulpiride	21	3	10	2100	ECOTOX
Metoprolol	7900	–	1000	7900	[60]
Diclofenac acid	1	3	10	100	[61]
17α-ethynylestradiol	181	1	100	1810	[62]
Dimethyl phthalate	1528	–	1000	1528	[63]
Diethyl phthalate	50	3	10	5000	ECOTOX

Notes: [a]: DEET: N,N-Diethylamino-3-methyl benzoyl amide; [b]: ECOTOX, https://cfpub.epa.gov/ecotox/.

Table 4
Water parameters of the WWTP effluents (mg L^{-1}; SUVA: L mg^{-1} m^{-1})

Site	COD	BOD_5	pH	TSS	SUVA	TP	TN	$N\text{-}NH_3$	$N\text{-}NO_3^-$	$N\text{-}NO_2^-$	F^-	Cl^-	SO_4^{2-}	Br^-
HLJ	49	11	7.13	15.4	1.04	0.22	8.85	5.48	0.92	0.47	0.5	66.9	84.4	–
JL	41	9	7.23	3.0	0.83	0.09	4.85	2.42	0.62	0.01	1.9	39.2	34.3	–
BJ1	16	4	7.41	3.1	0.8	0.17	5.31	2.53	1.46	–	0.8	169.0	123.1	1.3
TJ1	23	3	7.15	5.6	1.09	1.36	29.94	16.42	2.40	–	2.2	255.2	174.9	2.5
TJ2	34	–	7.22	0.4	0.02	0.09	15.81	8.29	2.93	0.49	1.7	241.1	117.9	1.1
HB1	36	8	7.46	4.6	0.48	0.29	6.91	4.57	0.84	–	1.8	383.0	374.3	1.6
HB2	74	19	7.14	40.1	2.10	0.64	6.49	3.69	0.26	0.61	1.3	312.9	155.6	2.9
SD	53	4	6.89	2.3	1.03	0.09	6.95	3.99	0.42	0.45	0.9	191.1	635.5	1.6
HN	36	–	7.48	2.2	0.27	0.34	3.48	2.17	0.44	0.04	26.7	843.8	230.0	–
SX	47	10	7.10	3.1	1.83	0.06	16.94	9.24	1.45	0.20	0.9	89.1	132.2	1.9
SHX	–	–	7.02	5.7	1.01	0.63	5.40	1.05	1.14	0.74	0.9	222.1	68.1	1.0
NMG	41	7	7.03	1.0	0.74	0.16	19.7	11.02	1.88	–	0.6	224.1	102.7	2.0

DON in wastewater effluents were of low-molecular-weight and hydrophilic [67]. Among the physicochemical parameters of the 12 effluent samples, only the concentrations of sulfate (SO_4^{2-}) showed a good correlation ($r = 0.811$) with the industrial wastewater ratio.

3.2. Regional distribution of the EOPs

The selected northern cities were separately located in ten provinces, including Heilongjiang, Jilin, Beijing, Tianjin, Hebei, Shandong, Henan, Shanxi, Shaanxi, and Inner Mongolia (Fig. 1a). There were 49 EOPs (i.e., 35 PPCPs, 2 steroid estrogens and 12 phthalates) detected with concentrations ranging from nanograms to micrograms per liter in the 12 WWTP effluent samples. The total EOP concentrations and the total EOP concentrations per treatment capacity in the 12 WWTPs are shown in Figs. 1b, c.

The total concentrations of the detected EOPs were 1652.7–18949.9 ng L^{-1}. Generally, the total concentrations of EOPs in the Beijing-Tianjin-Hebei region (5396.7–18949.9 ng L^{-1}) were higher than those in the other northern cities. This could be explained by the high population density and high amount of usage of pharmaceuticals and industrial products in the Beijing-Tianjin-Hebei region [10,52].

The dominant species varied among the different regions. Except in BJ, HN and SHX, PPCPs were the major species of detected EOPs in the effluents. HB1, which has a large proportion of industrial wastewater, had the highest concentrations of total PPCPs (16661.5 ng L^{-1}), including antibiotics (7568.7 ng L^{-1}) and other PPCPs (9092.8 ng L^{-1}). Steroid estrogens generally contributed a relatively low proportion of the total EOPs, and high concentrations of steroid estrogens occurred in only HLJ (575.0 ng L^{-1}) and JL (665.0 ng L^{-1}). In the BJ, HN and SHX effluents, phthalates made up a great portion of the total EOPs (Fig. 1b). The BJ effluent had the highest concentration of total phthalates (13584.3 ng L^{-1}).

3.3. Species of the EOPs

Of the 49 detected EOPs (Fig. 2), 49.0% had high detection frequencies of beyond 75.0%, and 28.6% had detection frequencies of below 50% in effluents. Sulfamethoxazole, azithromycin, carbamazepine, DEET, sulpiride, diclofenac acid, indomethacin, and 17α-ethynylestradiol were detected in all samples. The detection frequencies of erythromycin, clarithromycin, roxithromycin, clindamycin, nalidixic acid, ofloxacin, mefenamic acid, clofibric acid, dimethyl phthalate, and diethyl phthalate were all above 90.0%.

Of the 42 PPCPs, 35 compounds (including macrolides antibiotics, quinolones antibiotics, sulfonamide antibiotics, and other pharmaceuticals) were detected. The detection frequencies of macrolides antibiotics, quinolones antibiotics, sulfonamide antibiotics, and other pharmaceuticals were >91.5%, >75.0%, 36.4%, and >41.5%, respectively. Tetracycline antibiotics and penicillinase antibiotics were not detected. The detection frequencies of erythromycin, clarithromycin, roxithromycin, clindamycin, nalidixic acid, ofloxacin, mefenamic acid, and clofibric acid were above 90.0%. Among the detected PPCPs, metoprolol showed the highest concentration (maximum value 2310.0 ng L^{-1}, mean value 798.0 ng L^{-1}, median value 787.5 ng L^{-1}) in the effluents of all WWTPs. The levels of metoprolol in this study were much higher than those reported in Switzerland (160–240 ng L^{-1}) [36], Korea (3 ng L^{-1}) [15], the UK (69 ng L^{-1}) [18], and highly urbanized Chinese regions (62–166 ng L^{-1} in Beijing, 13.2 ng L^{-1} in Changzhou, and 52.3–58.7 ng L^{-1} in Shenzhen) [31]. There were six other PPCPs that had high mean concentrations of beyond 200 ng L^{-1} (median concentration >110 ng L^{-1}), including carbamazepine (597.5 ng L^{-1}), sulpiride (543.5 ng L^{-1}), sulfamethoxazole (311.0 ng L^{-1}), diclofenac acid (307.6 ng L^{-1}), ofloxacin (195.0 ng L^{-1}) and norfloxacin (190.3 ng L^{-1}). Carbamazepine is persistent in aquatic environments and is often present at a high level. For example, the mean concentration of carbamazepine in WWTP effluents was 580 ng L^{-1} in Spain [21], 2499 ng L^{-1} in the UK [18], 832 ng L^{-1} in EU-wide [24], 173 ng L^{-1} in Western Greece [68], and 102–332 ng L^{-1} in Beijing and Harbin in China [69,70]. Sulpiride is a typical antipsychotic agent and has a relatively low order of acute toxicity. There is a lack of information on the occurrence of sulpiride in WWTPs and aquatic environment. The concentrations of sulpiride in Chinese WWTP effluents were 102.0 ng L^{-1} in Harbin, 134.0–208.0 ng L^{-1} in Beijing, 7.8 ng L^{-1} in Changzhou, and

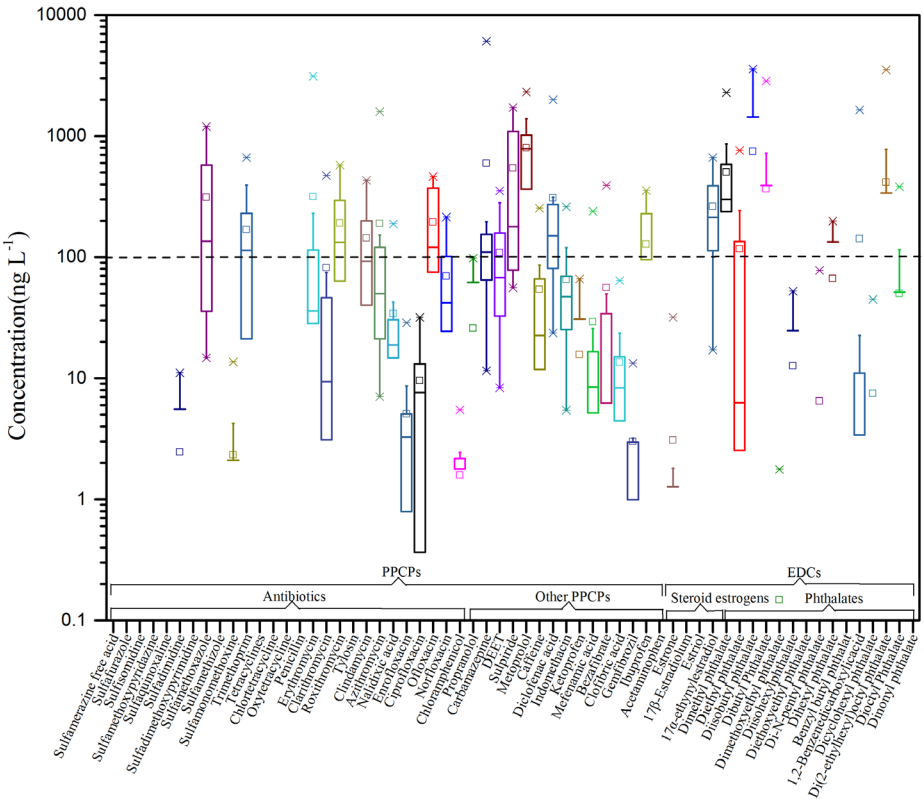

Fig. 2. Individual concentrations of the 61 EOPs in the WWTPs.

80.0–84.7 ng L^{-1} in Shenzhen [31,70]. The levels of sulfamethoxazole in this study were also higher than those detected in the UK (10 ng L^{-1}) [18], Korea (57 ng L^{-1}) [15], and EU-wide (142 ng L^{-1}) [24]. Diclofenac acid had a mean concentration of 307.6 ng L^{-1}, which was lower than the concentrations in Italy (800 ng L^{-1}) [71] and western Greece (381 ng L^{-1}) [68] but higher than those in Korea (55 ng L^{-1}) [15], the UK (98 ng L^{-1}) [18], and the southern cities of China (120–143 ng L^{-1}) [72]. Ofloxacin is a broad-spectrum quinolone/fluoroquinolone antibiotic. Higher concentrations of ofloxacin in Beijing (651–1561 ng L^{-1}) [34] and Shanghai (195.9–1976.1 ng L^{-1}) [33] in China have been reported. Relatively low concentrations of ofloxacin were reported in the Jiulongjiang River Basin, China (6–53 ng L^{-1}) [73]. Norfloxacin, as a synthetic chemotherapeutic antibacterial agent, was of low concentration in the Jiulongjiang River Basin, China (13–172 ng L^{-1}) [73], and Harbin, China (60 ng L^{-1}) [42].

Of the 4 steroid estrogens, only estrone and 17α-ethynylestradiol were detected. In all samples, 17α-ethynylestradiol was detected with relatively high concentrations (maximum value 665.1 ng L^{-1}, mean concentration 261.4 ng L^{-1}, median value 213.0 ng L^{-1}). The levels of 17α-ethynylestradiol were much higher than those reported in Italy (mean concentration 23.6 ng L^{-1}) [15] and France (ND-2.1 ng L^{-1}) [38]. The levels of estrone were low, with a maximum value of 31.8 ng L^{-1} and an mean value of 7.4 ng L^{-1} (detection frequency 41.7%). The levels of estrone were 32 ng L^{-1} in Italy [15] and 3.0±3.4 ng L^{-1} in Sweden [27].

Of the 15 phthalates examined, 13 were detected. Dimethyl phthalate and diethyl phthalate had high detection frequencies of above 45.0%. Dimethyl phthalate had the highest concentration (maximum value 2281.0 ng L^{-1}, mean value 502.6 ng L^{-1}, median value 300.5 ng L^{-1}) among the 13 detected phthalates. The concentrations of dimethyl phthalate in this study were much higher than those reported in France (ND-60 ng L^{-1}) [74], Germany (ND ng L^{-1}) [13], Austria (ND-0.19 ng L^{-1}) [41], and Harbin, China (ND-1.52 ng L^{-1}) [42].

3.4. Correlations between water quality parameters and the levels of EOPs

As shown in Fig. 3, the total concentrations of all detected EOPs were significantly positively correlated with the concentrations of Nitrite-N. Weak correlations between the total EOP concentrations and concentrations of TOC, ammonium, Cl^-, or SO_4^{2-} were observed.

The concentrations of some PPCPs, such as chloramphenicol, metoprolol, bezafibrate, sulpiride, caffeine, and roxithromycin, had strong positive correlations with TN (r = 0.48–0.85) and total phosphorus (TP) (r = 0.37–0.67). The concentrations of PPCPs were positively correlated with TN, as previously reported. Wang et al. found that in WWTP effluent-receiving rivers, the total concentration of pharmaceuticals was positively correlated with the TN and TP in the river [31]. Our study confirmed again that WWTP effluent is an important pathway for PPCPs entering into natural water bodies. The correlations between the PPCP concentrations and the concentrations of TOC, ammonium, Cl^-, or SO_4^- were weak.

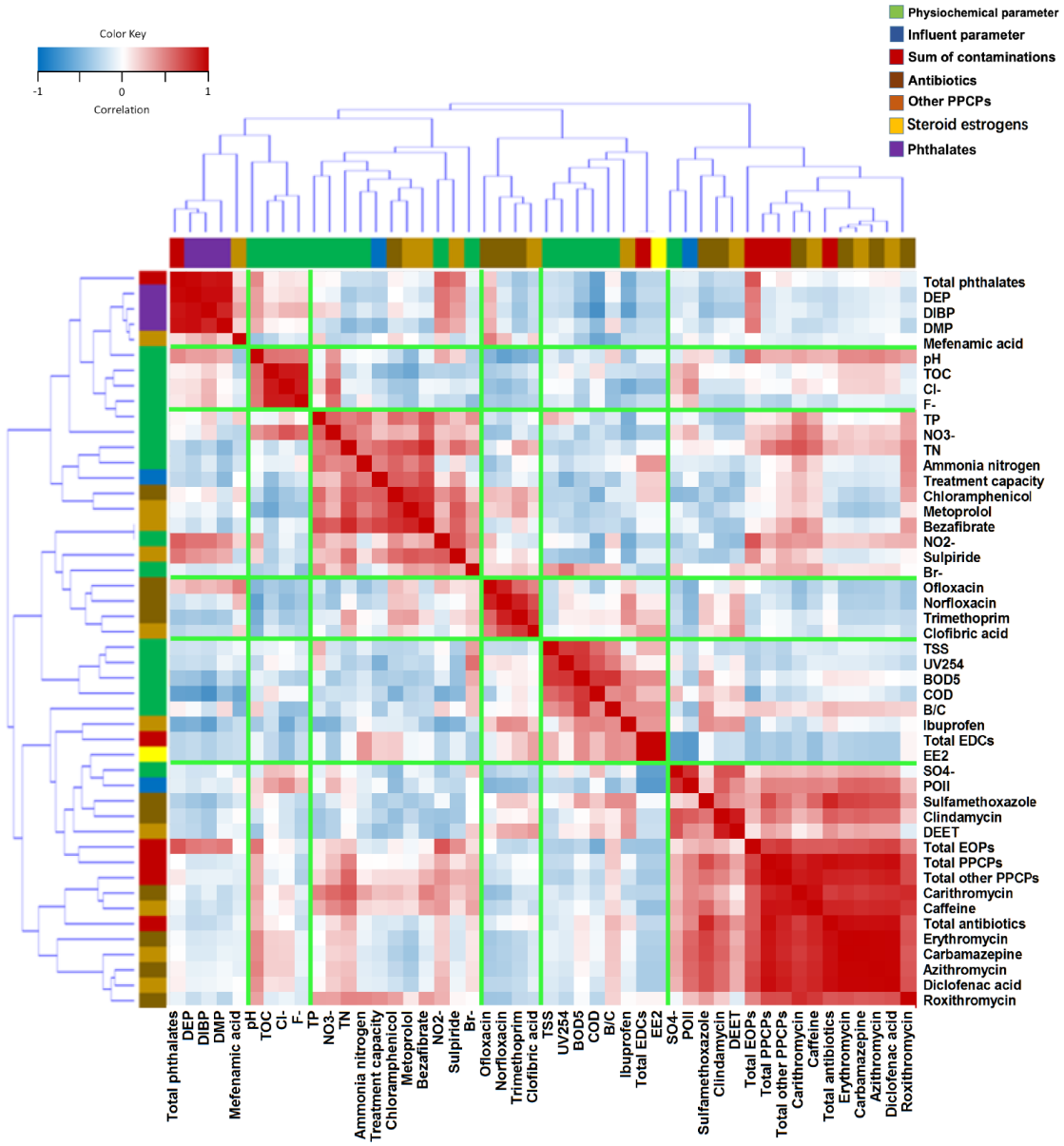

Fig. 3. Correlations between the effluent parameters and EOPs (Red colors: significant positive correlations; blue colors: significant negative correlations). The depth of color represents the intensity of the correlation. EE2 (17α-ethynylestradiol), DMP (dimethyl phthalate), DEP (diethyl phthalate), DIBP (diisobutyl phthalate), and POII (proportion of industrial sewage in influent).

The concentrations of clindamycin, diclofenac acid, DEET, clarithromycin, erythromycin, carbamazepine, or SO_4^{2-} were found to be positively correlated with the proportion of industrial wastewater in the influents, so, presumably, most of these compounds could come from industrial sources [75].

The total concentrations of EDCs were positively correlated with the concentrations of ammonia nitrogen and BOD_5. The concentrations of 17α-ethynylestradiol were significantly related to the levels of BOD_5, COD, BOD_5/COD ratios, TSS and UV_{254}. The total concentrations of phthalates and the individual concentrations of dimethyl phthalate, diethyl phthalate and diisobutyl phthalate showed a negative correlation with the COD.

Correlation analysis was performed among the EOPs. The concentrations of nine compounds (i.e., roxithromycin, diclofenac acid, azithromycin, carbamazepine, erythromycin, caffeine, clarithromycin, sulfamethoxazole, or dimethyl phthalate) had significantly positive correlations with the total amount of all detected EOPs ($r > 0.65$) (Fig. 3). The concentrations of roxithromycin, azithromycin, carbamazepine, and erythromycin also had strong positive linear correlations with the total amount of all detected PPCPs in river water [76]. In addition, diclofenac acid, azithromycin, carbamazepine, and erythromycin were significantly positively correlated with each other ($r > 0.90$). The levels of dimethyl phthalate, diethyl phthalate, and diisobutyl phthalate had significantly positive correlations with the total levels of phthalates.

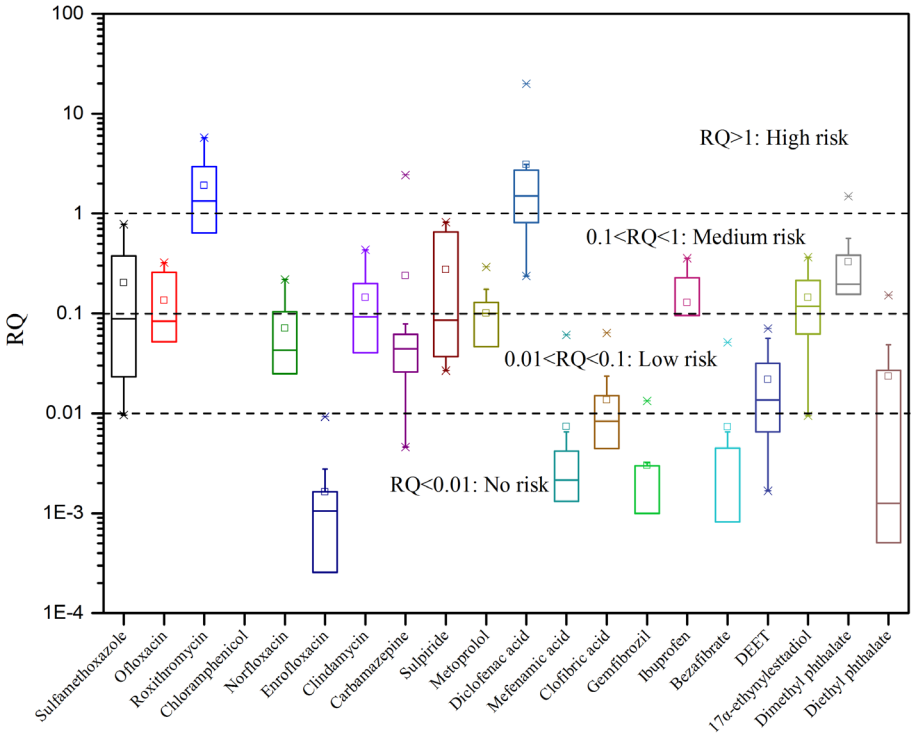

Fig. 4. RQs for the 20 EOPs in the WWTP effluents (RQ = 0.01–0.1, low risk; RQ = 0.1–1 , medium risk; RQ > 1, high risk).

3.5. Ecological risk assessment and chemical indicators

Of the detected EOPs, 20 EOPs with relatively high concentrations, detection frequencies and strong potential toxicities were selected for the ecological risk assessment. Three risk classes were established according to the RQ values: 'low risk' (RQ = 0.01–0.1), 'medium risk' (RQ = 0.1–1), and 'high risk' (RQ > 1) [76]. As shown in Fig. 4, diclofenac acid and roxithromycin posed high risks (RQ > 1) to aquatic organisms, and their probabilities of the high risk in the 12 WWTPs were 66.7% and 58.3%, respectively. Diclofenac acid was identified as the compound with the highest potential environmental risk in a recent study, which investigated 55 PPCPs in municipal WWTPs in Greece and India [77].

The probabilities of sulfamethoxazole, ofloxacin, clindamycin, sulpiride, ibuprofen, 17α-ethynylestradiol, and dimethyl phthalate causing medium or high risk in the 12 WWTPs were 50.0%, 41.7%, 50.0%, 50.0%, 50.0%, 58.3%, and 83.3%, respectively. Sulfamethoxazole, ofloxacin and roxithromycin showed high or medium risk to aquatic organisms [9,78,79]. Based on the correlations between concentrations of the EOPs and their potential ecological risks, diclofenac acid, roxithromycin, sulfamethoxazole, and dimethyl phthalate could be selected as surrogates indicating the EOP contamination in the WWTPs of the northern cities in China.

4. Conclusions

Of the investigated 61 typical EOPs (42 PPCPs and 19 EDCs) in the effluents of 12 WWTPs in northern cities of China, the EOPs with high levels and detection frequencies included metoprolol (798.0 ng L^{-1}, 83.3%), carbamazepine (597.5 ng L^{-1}, 58.3%), dimethyl phthalate (502.6 ng L^{-1}, 83.3%), sulpiride (543.5 ng L^{-1}, 66.7%), sulfamethoxazole (311.0 ng L^{-1}, 58.3%), diclofenac acid (307.6 ng L^{-1}, 66.7%), 17α-ethynylestradiol (261.4 ng L^{-1}, 83.3%), ofloxacin (195.0 ng L^{-1}, 58.3%), and roxithromycin (190.3 ng L^{-1}, 58.3%). PPCPs were the predominant species and contributed to approximately half of the total EOP concentrations detected in the WWTPs. The Beijing-Tianjin-Hebei regions had higher total concentrations (5396.7–18949.9 ng L^{-1}) of EOPs than did the other northern cities. The concentrations of most EOPs showed positive correlations with the TN levels of the effluents. Based on the correlations of concentration among the EOPs and their potential ecological risks, diclofenac acid, roxithromycin, sulfamethoxazole, and dimethyl phthalate could be selected as chemical indicators of EOP contamination in the WWTPs of the northern cities in China.

Acknowledgments

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